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Adding Stochastic Behavior to Deterministic Simulation Package HULL

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13. ABSTRACT *(Maximum 200 words)*

A study to investigate the stochastic variation in material failure mechanics of a typical high hardness armor (HHA) against tungsten penetrator problems was conducted. The HULL package was modified for simulation studies, and results from two different sets of calculations, each with a different randomness level, showed a relationship between the final lengths (between stations) and the prescribed randomness.

Since higher percent deviation is likely associated with the higher failure rate of the target material, thus, at lower percent deviations, there is less penetration into the target and more compression of the penetrator, resulting in a smaller final length. Hence, the relationship seems to be a result of the compressive state of the penetrator rather than a result of its erosion. This relationship is likely to be present also in a more rigorous calculation with a Lagrangian-based formulation.

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1. INTRODUCTION

Ballistic experiments, like most other experiments, usually have random errors associated with measurements. The errors come from many factors, such as differences in operational procedures, environmental conditions, and material properties. Of these, operational procedures can usually be maintained constant. However, there are uncertainties associated with the measured variables, such as yaw, pitch, impact velocity, etc., which can affect the response variables, e.g., residual mass, residual velocity, etc. In addition, there is little that can be done to control environmental conditions except to monitor the weather conditions.

An additional set of measured variables that are generally not treated well in ballistic experiments is the material properties. In most cases, absence of detailed descriptions about the properties adds a source of uncontrolled error in the response variable. In some cases, material property variation could be the primary factor, since, in general, materials are neither homogeneous nor isotropic but vary from piece to piece and point to point within a sample. These departures from homogeneity may be the result of local chemistry variations, microstructure variation, textures developed during processing, or other factors. Each definitely contributes to the scattering in the experimental results.

The purpose of this report is to investigate the way variations in material properties might affect the outcome of a series of ballistic penetration computations. As currently configured, Eulerian as well as Lagrangian computational codes suitable for penetration computations assume that the materials are homogeneous and isotropic. Additionally, other than stress/strain criteria for failure, there are no other explicit failure criteria built in simulation packages such as HULL. A number of Government laboratories and universities are striving to model such failure mechanisms as adiabatic shear failure (Hauver et al. 1992). These models start at the most fundamental microscopic level (for instance, the inclusion of the "shear band" failure mechanism in the code); their incorporation in a large computational code that can run to completion within memory and time constraints is not a certainty.

This study attempts to attack the problem from the opposite end, zeroth-order macroscopic direction. It is a first attempt to add stochastic variations to the material property subroutines in an otherwise deterministic simulation package. The hope is to gain insight on the level of modeling required for accurate prediction of ballistic results and to provide researchers with a direction for further refinement.

As a sample problem, the relatively simple case of a long rod penetrator striking an oblique, finite-thickness plate was computed with and without stochastic variations in material properties. The results are presented and discussed.

2. METHOD

The HULL code handles material failure by giving the user the option to choose from the following three different failure criteria: (1) the maximum principal stress criterion for spall failure in plane strain (FAIL=1 in the HULL input deck); (2) the maximum principal strain criterion added for failure in plane stress or ductile failure (FAIL=1 STRAIN=1) (in the present study, both ultimate stress and strain were used to initiate material failure); (3) the triaxial states, based on a P/Y model (a material failure domain to strain-stress relationship), used to determine whether fracture can occur. The third is most complex and debatably more realistic in behavior but requires extensive material property data (FAIL=2 STRAIN=1) (Matuska, Osborn, and Piburn 1991). All these failure models result in material separation or void inclusion. In HULL, the most numerically reliable method of simulating these conditions has been to "inject" air into the calculation as the "void" material.

During the initial stage of this study, the first failure model was used. Since this model was elementary, the second model was eventually employed. The third model uses more detailed description, but since extensive material property data were required, it was not possible to implement at this time. Consequently, this study proceeded primarily with the second failure model.

Careful study of the simulation package HULL revealed that the material failure mechanism is described in subroutines "hydro" (in subprogram hull) and "mgrun" (in subprogram eos), where the stress and strain are first calculated in the usual deterministic way and then compared with the ultimate stress or strain to determine whether the particular computational material cell fails. The challenge was to find a way to add stochastic behavior into this otherwise deterministic failure mechanism.

With a single specimen of material undergoing a uniaxial strength test, there is the familiar stress-strain relationship as shown in Figure 1. Here the material stretches linear-elastically until it reaches a certain yield stress. After this point, the relationship is no longer elastic. The material continues to elongate until it reaches a point where it can no longer sustain an increase in stress, and there it breaks or fails. For a single test, one obtains a smooth stress-strain curve. But the materials are not really uniform; they are not the same from sample to sample. The differences may be caused by chemical inhomogenieties, texturing caused by mechanical working during processing, and so forth. Consequently, there will be variations in this curve, and the location of the failure point is not the same from specimen to specimen.

To quantify this variation, a variable called the "probability of failure" as a function of stress was used. This implies that there is a certain probability of failure associated with each stress level. The material does not fail immediately when a certain ultimate stress is reached, but rather the probability of failure increases around that stress level σ_{ij} at certain cell location ij within an interval δ, as shown in Figure 2. A certain statistical distribution of this failure behavior is assumed, where the probability of failure ranges from 0 (i.e., no failure) to 1 (i.e., certain failure). With this statistical distribution, it is possible to bring some stochastic behavior into the otherwise deterministic failure mechanism with the following steps:

(1) calculate the stress in a particular material cell being looked at, sequentially through all cells in all coordinates,

(2) determine the probability of failure from the statistical distribution of failure as a function of stress,

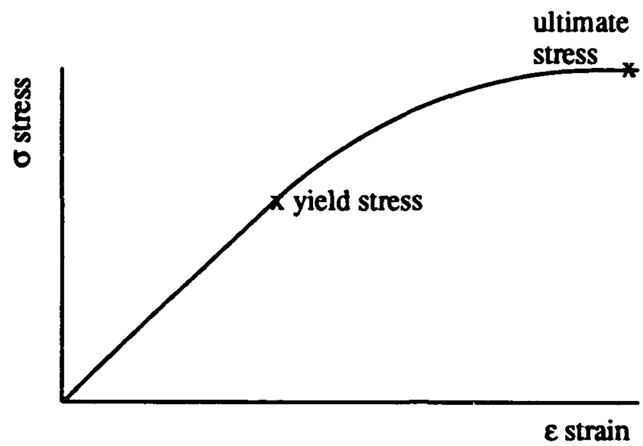

Figure 1. The ordinary stress-strain relationship.

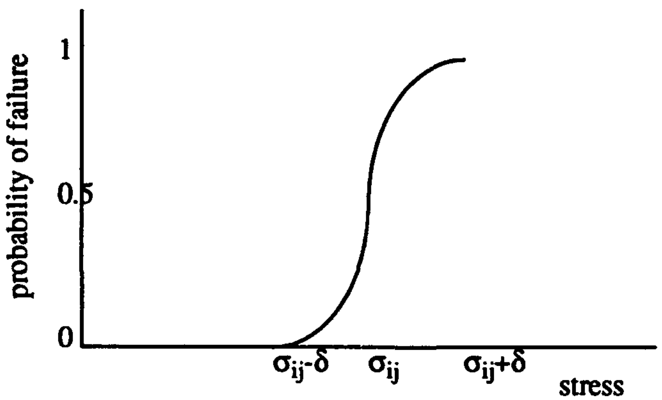

Figure 2. Probability of failure as a function of stress.

(3) draw a random number from a uniform random number (URN) routine (the number falls uniformly between 0 and 1),

(4) compare the probability of failure with the random number: if URN <= probability of failure, then the material cell fails.

In the stochastic treatment of the relationship between stress and material failure, the amount of stress necessary to cause such a failure becomes a random variable which is assumed to be normally distributed with an expected value equal to the original stress threshold. Other distributions can be applied if there are logical reasons to do so; however, in this case the normal assumption seems intuitively applicable. The normal probability density function is the familiar bell-shaped curve; its cumulative distribution function results from the integration of this probability density function (Walpole and Myers 1978). For this procedure, the cumulative distribution function was truncated so that it covered a sufficient range of stress ($\pm\delta$ in Figure 2) without reaching infinite values. This truncated normal distribution was then used as the functional relationship between the amount of stress and the probability of material failure in all the computational cells.

A uniform random number is chosen from a routine which uses the computer system time as the seed for initiation of calculation. This is a traditional technique used in Monte-Carlo simulations. It provides equally likely numbers between 0 and 1 which can be compared with some cumulative distribution function. The computation follows the previously mentioned steps to decide whether the material in a particular computational cell fails. If it does, then a void is inserted into that cell. In this example, if the probability of material failure from the cumulative normal distribution function is 0.9, then approximately 9 times out of 10 the uniform random number will be less than or equal to the probability of failure. Thus, in 10 replications of the model, there will be approximately 9 failures. To ensure sufficient stochastic effects, the penetration problem was repeated 100 times on a Cray-2 computer, calculating out to 200 μs physical time. For each replication, the final locations of both the tip and the tail of the penetrator were determined, and the resulting lengths were statistically analyzed.

An additional algorithm to add stochastic behavior to the strain fail criterion has been formulated and is similar to the one for the stress fail mentioned previously.

Later, some modifications were made. This will be described in the next section.

3. RESULTS

The problem chosen for the statistical study is a tungsten alloy penetrator against a high hardness armor (HHA) plate (Magness, Farrand, Rensselaer 1986). An HHA plate of 3.175-cm (1.25 in) thickness at 60° obliquity was tested against a tungsten alloy penetrator (radius=0.414 cm, length=10.26 cm, L/D=12.39) at 1.1 km/s (see Appendix for the input deck).

The initial configuration is shown in Figure 3.

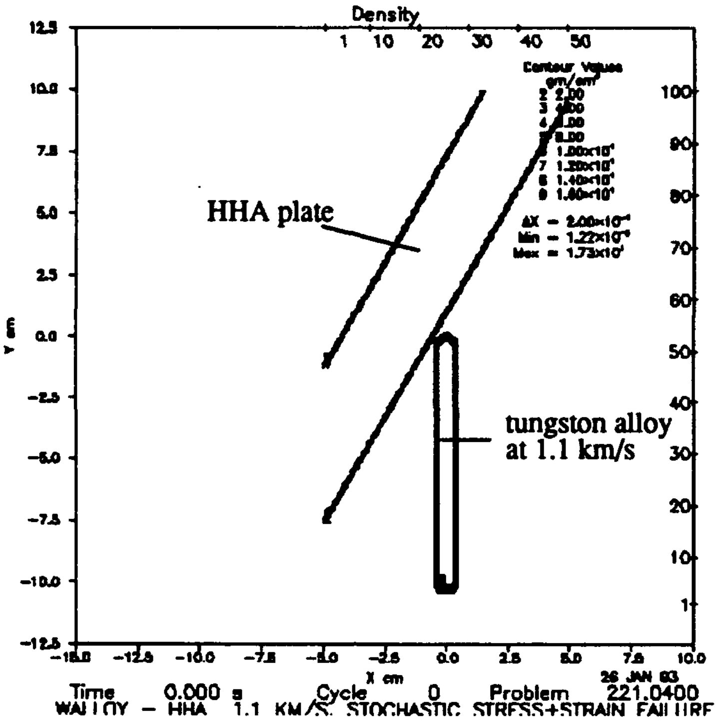

Figure 3. Armor example at 0 μs.

The computation created data dumps every 50 μs, until 200 μs was reached. These were plotted and are displayed in Figures 4-7.

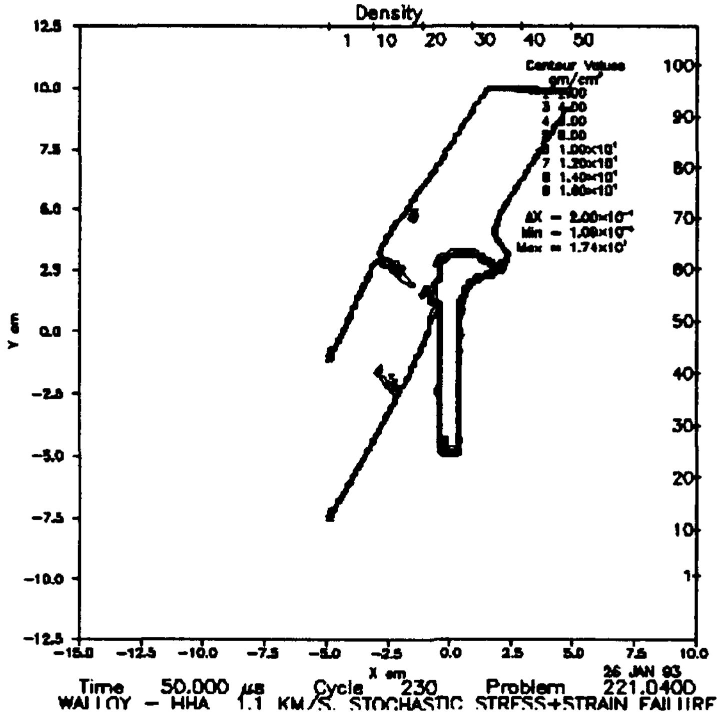

Figure 4. Armor example at 50 μs.

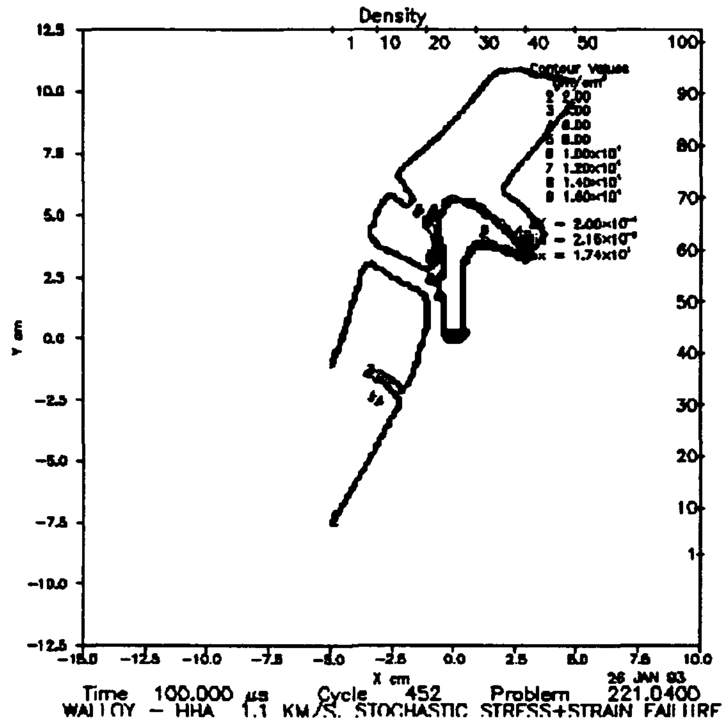

Figure 5. Armor example at 100 μs.

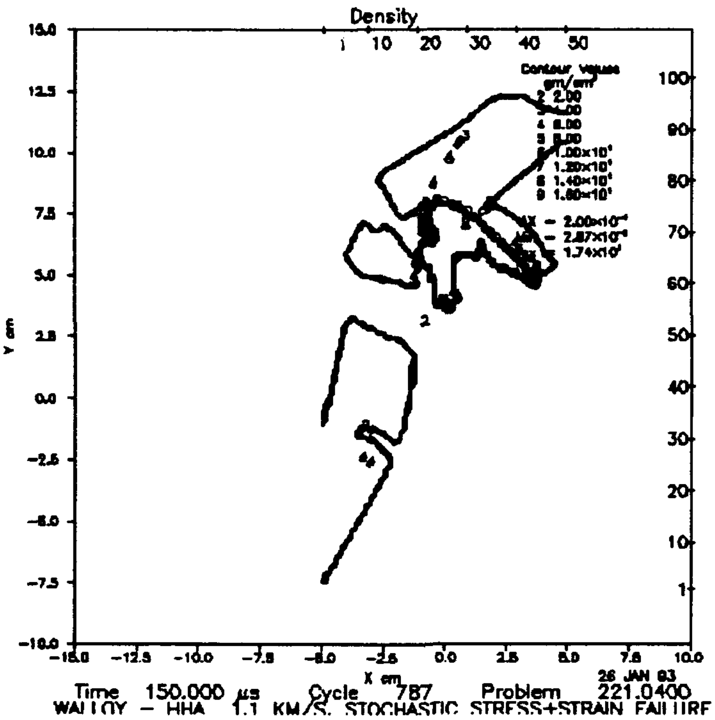

Figure 6. Armor example at 150 μs.

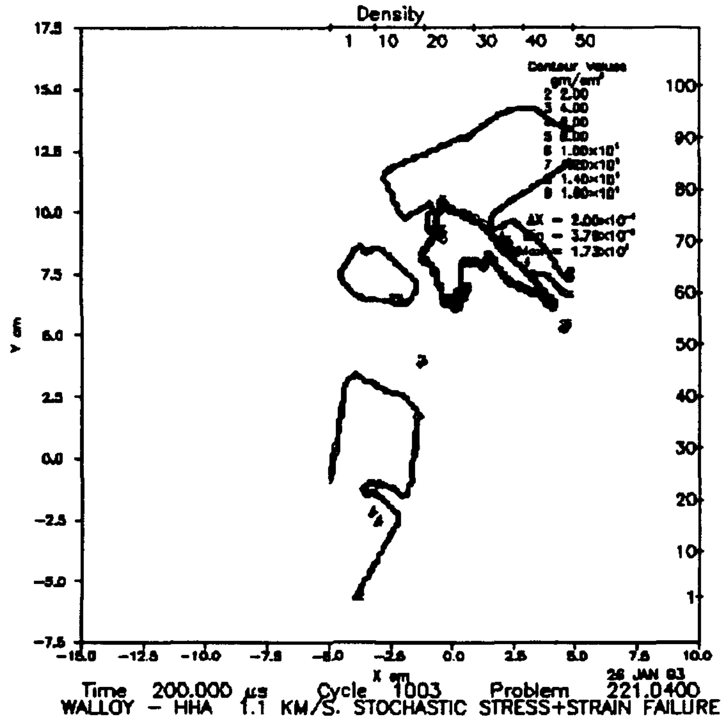

Figure 7. Armor example at 200 µs.

For each of the three percent deviations associated with the cumulative distribution, namely ultimate stress ±5%, ±10%, and ±15% (±δ in Figure 2), the calculation was carried out 100 times. A calculation with 0% deviation, i.e., without any statistical randomness, was also carried out to serve as a basis for comparison. The final lengths of the penetrator after 200 µs were collected and statistically processed, as displayed in Table 1.

Table 1: Final Lengths vs. Initial Randomness (First Calculation)

Percent Dev. of the cumulative normal distribution	Median of the 100 computed final lengths (cm) btw stations 1 and 2	Standard Dev. of the 100 computed final lengths
0.00	2.2488	
0.05	2.24560	0.074155
	2.23710	0.078487
	2.24365	0.073094
0.10	2.28730	0.076906
	2.27935	0.078190
	2.28375	0.074500
0.15	2.29045	0.071916
	2.28455	0.077485
	2.29350	0.079646

Notice that, for each percent deviation of the cumulative normal distribution, the patched HULL has been run 100 times. But, in order to see also the statistical character of this computation, this has been done three times for each of the percent deviations, as displayed in the three rows for each percent deviation in Table 1. The results indicate a distribution of final penetrator lengths, and this randomness shows a mild trend corresponding to the trend in the percent deviation of the cumulative normal distribution between the probability of failure and stress/strain. The in-group randomness (last column in Table 1) remains about constant.

After some deliberation on these results, it was noticed that, while the seed (which is required to initiate the calculation for a random number) used in the previous computation did change randomly, which is desirable, the randomness was more than necessary. While the computation

runs sequentially in the spacial coordinates, when the computation sweeps into the next time step, the seed used in each material cell may not be exactly the same seed used during the previous time step at exactly that same location. This variation along the time axis did not seem to correctly describe the variation in the material property. In effect, this numerical process tended to homogenize the material properties. Therefore, the next attempt removed this time-dependent variation.

One way to implement the randomness into the computation without a time-dependent randomness is to reset the seed every time step at the same material cell to be exactly the same as the value at the beginning. The computation results from this formulation are displayed in Table 2.

Table 2: Final Lengths vs. Initial Randomness (Second Calculation)

Percent Dev. of the cumulative normal distribution	Median of the 100 computed final lengths (cm) btw stations 1 and 2	Standard Dev. of the 100 computed final lengths
0.00	4.1682	
0.05	4.18219	0.02968
0.10	4.18715	0.01083
0.15	4.20477	0.00793

(Note: The grid and station locations have been modified from Table 1 to Table 2 during the evolution of the study, such that the final lengths between stations show different values. But the statistical meaning of the study is not changed.)

The results in Table 2 show some trend relationship between the randomness in the final penetrator length and the randomness inherent in cumulative normal distribution function. Since

higher percent deviation is likely associated with higher fail rate of the target material, thus, at lower percent deviations, there is less penetration into the target and more compression of the penetrator, resulting in a smaller final length. So the relationship between the randomness in the failure model and the randomness in the final length seems to be a result of the compression of the penetrator rather than a result of its erosion.

Furthermore, since the difference is so small, the randomness itself may be covered by other noise such as that from the computational accuracy. In addition, the in-group randomness (last column) shows a clearer trend than that in Table 1.

The differences in the median final lengths in Table 2 from those in Table 1 reflect the changes that occurred in the input geometry (grid arrangement and station locations) during the evolution of development (see Appendix). These difference are not significant toward the understanding of the statistical behavior of the material strength.

4. DISCUSSIONS

Two different methods to add stochastic behavior to the deterministic simulation package HULL were investigated.

The results from the first method, continued regeneration of random numbers with a new seed at each time step, showed certain relationship between the randomness associated with the cumulative normal distribution function and the randomness in the final length of the penetrator. However, the varying seed in each cell in time is more than necessary. A reasonable fix was to remove the variation in time.

The results from the second method, resetting the seed value to its initial value for all subsequent time steps, showed a mild relationship, which seemed to be driven more by the compression of the penetrator than by its erosion. In addition, there is also a trend in the in-group

randomness (last column) relative to the randomness in the failure model. This trend was small and possibly tainted by faint computational noises.

Further study in the last approach has revealed the fact that the computational grid in an Eulerian formulation does not follow the material. In other words, the Eulerian grid does not capture the material property in the same cell. In an Eulerian code such as HULL, the calculation sweeps through grid nodes in the Eulerian space. Modifications to the code change the calculation at each grid point in the Eulerian grid but not the material. So this formulation does not provide a random material property at the same material location, which is unfortunately essential for the study of the material failure.

In order to modify the calculation in association to each certain material particle, a more sophisticated way must be formulated, such that the calculation will follow the material instead of merely the Eulerian grid. Therefore, the next reasonable approach is to find a way to add the stochastic variation in a Lagrangian fashion, which is not quite as straightforward in an Eulerian code. Furthermore, Lagrangian codes usually have limitations in dealing with failure problems.

However, since Table 1 (first method, which has more randomness than necessary) and Table 2 (second method) both showed a trend between the final lengths and the initial randomnesses in the model, it is likely a similar trend will also be present in a better formulated calculation based upon a Lagrangian grid.

This study exposed some inadequacies in two different approaches and provided illumination for future study in the statistical analysis of material strength.

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APPENDIX:

TYPICAL INPUT DECKS

FOR THE FIRST AND SECOND CALCULATIONS

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A-1. INPUT DECK FOR THE FIRST CALCULATION

A typical input file to initiate the HULL run, called keel.in, follows:

```
keel prob 00221.0100
    dimen=2 geom=1
    imax=50 jmax=100
    fail=1 strain=1
    nm=3 air=1 hha=2 walloy=3
    visc=1 dvisc=2
    nop=2 nstn=2
header
    walloy - hha @ 1.1 km/s, stochastic stress+strain failure
mesh
    x0=-5 xmax=5 y0=-11 ymax=9
generate
package walloy v=1.1e5
    rectangle x1=-.414 x2=.414 y1=-10.26 y2=-.414
    circle xc=0. yc=-0.414 radius=0.414
package walloy v=1.1e5
    circle xc=0. yc=-0.414 radius=0.414
package hha
    rectangle x1=-50. x2=50. y1=.5 y2=3.675
    xcc=0. ycc=0. angla=60
package air
    rectangle fill

stations
    xs=0.0 y1=-8., 0.
end
```

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A-2. INPUT DECK FOR THE SECOND CALCULATION

A typical input file to initiate the HULL run, called keel.in, follows:

```
keel prob 00221.0200
    dimen=2 geom=1
    imax=50 jmax=100
    fail=1 strain=1
    nm=3 air=1 hha=2 walloy=3
    visc=1 dvisc=2
    nop=2 nstn=2
header
    walloy - hha @ 1.1 km/s, stochastic stress+strain failure
mesh
    x0=-5 xmax=5 y0=-10 ymax=10
generate
package walloy v=1.1e5
    rectangle x1=-.414 x2=.414 y1=-10.26 y2=-.414
    circle xc=0. yc=-0.414 radius=0.414
package walloy v=1.1e5
    circle xc=0. yc=-0.414 radius=0.414
package hha
    rectangle x1=-50. x2=50. y1=.5 y2=3.675
    xcc=0. ycc=0. angla=60
package air
    rectangle fill

stations
    xs=0.0 y1=-10.26, 0.
end
```

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